Development and Utilization of Regional Oceanic Modeling System (ROMS) & Delicacy, Imprecision, and Uncertainty of Oceanic Simulations: An Investigation with ROMS

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LONG-TERM GOALS

Our long-term goal is the continuing evolution of the Regional Oceanic Modeling System (ROMS) as a multi-scale, multi-process model and its utilization for studying a variety of oceanic phenomena. The dynamical processes span a range from turbulence to basin-scale circulation. A complementary goal is to explore, document, and explain the nature of the delicacies of the simulations for highly turbulent oceanic circulation. We expect that our experience will be relevant to analysis and forecast uncertainties for other atmospheric and oceanic simulation models. These activities are of interest to ONR through its core, DRI, and NOPP programs, including submesoscale parameterization (AESOP), strong internal waves (NLIWI), high-resolution air-sea interaction (HIRES), tropical cyclones, sediment transport, and horizontal mixing (LATMIX).

OBJECTIVES

Our core objectives are code improvements and oceanographic simulation studies with the Regional Oceanic Modeling System (ROMS). The targeted problems are submesoscale wakes, fronts, and eddies; nearshore currents; internal tides; regional and Pacific eddy-resolving circulations and their low-frequency variability; mesoscale ocean-atmosphere coupling; and planetary boundary layers with surface gravity waves. To address these problems we are making ROMS more of a multi-process, multi-purpose, multi-scale model by including the coupling of the core circulation dynamics to surface gravity waves; sediment resuspension and transport; biogeochemistry and ecosystems; non-hydrostatic large-eddy simulation; and mesoscale atmospheric circulation, and providing a framework for data-assimilation analyses (led by others). Our major algorithmic objectives are cross-scale grid-embedding in turbulent flows; improved accuracy in the Boussinesq approximation with a realistic Equation of State (EOS); accurate advection; dynamically adaptive, vertical coordinates; surface-wave-averaged vortex force and Lagrangian transport; and parameterization of wave-breaking and other mixing effects. Finally, we continue to further improve the pre- and post-processing tools and on-line documentation for ROMS.

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A parallel objective is to establish the characteristics of model uncertainty in ROMS for realistic simulation of complex flows, as an intrinsic model contribution to analysis and forecast errors. The premise is that defensible alternative model designs — in parameter values, subgrid-scale parameterizations, resolution, algorithms, topography, and forcing data — may often provide a range of answers comparable to the model-measurement discrepancies, although as yet this kind of sensitivity is largely undocumented. A corollary is that alternative models may have a sizable degree of mutually irreproducible answers for complex flows. We hypothesize that at least some part of the model-to-measurement and model-to-model differences may be irreducibly inherent in the mathematical structure of modern simulation models.

APPROACH

Computational simulation of currents and material distributions is an important and evolving tool in the geosciences. ROMS is a loosely coordinated modeling approach with a substantial international community of developers and users (www.myroms.org). It uses a generalized terrain-following coordinate and is is implemented as a modern, efficient parallel code, accompanied by an infrastructure of pre- and post-processing and visualization tools. ROMS provides a test-bed for some of the most innovative algorithms and parameterizations in ocean modeling, and it is now the most widely used model among academic researchers for regional, high-resolution simulations of highly turbulent flows. At UCLA we are among the lead architects of ROMS. Our approach is problem-driven: the algorithmic formulation and code implementation are advanced to meet the requirements for simulating particular processes and phenomena.

To test the hypothesis of irreducible uncertainty, we use ROMS to evaluate model sensitivity with respect to plausible variations in several test configurations: flow past idealized sea mounts; realistic Pacific basin circulation comparable to present and near-future operational analysis configurations; and Western- and Eastern-Pacific nested-subdomain currents and eddies with mesoscale and submesoscale flow-topography interaction.

WORK COMPLETED

Our work is comprised of algorithm design, code implementation, forcing and topographic data preparation, performing and analyzing simulations, and theoretical interpretation.

In the past year we have worked on the following circulation regimes and phenomena: decadal Pacific circulation; equilibrium regional circulations along the U.S. West Coast, central Alaska, Central America, South America, the Kuroshio, and the Gulf Stream; mesoscale eddy detection and tracking; submesoscale surface fronts, filaments, and eddies; topographic current separation, form stress, and submesoscale vortex generation; surface waves and nearshore currents in North Carolina and Southern California; internal tides in the South China Sea and Southern California; surface wave influences on the oceanic surface layer; bubbles generated by wave breaking; and mesoscale air-sea coupling. The algorithmic work has been on adapting the oceanic equation of state for split-explicit time stepping of barotropic and baroclinic modes; accurate time-stepping for the bottom boundary layer in shallow water ($\sim$ meters) and wake flows past topography; open boundary conditions for highly turbulent flows; incorporating surface wave effects in ROMS; diagnosing spurious diapycnal mixing due to advection errors and designing remedies; a new model of a size-distributed bubble population; a new multi-scale data assimilation methodology (Li *et al.*, 2010); and the design and

preliminary evaluation of test-bed configurations for the simulation delicacy investigation.

RESULTS

We present a few highlights briefly. The Publication section provides a complete view of finalized results.

Grid Nesting and Open Boundary Conditions: Global oceanic models are limited in their grid resolution, hence their completeness in the included circulation processes. Regional models do not have such an inherent limitation, but they do require accurate, computationally well-behaved open-boundary conditions to achieve realistic mean circulations. Furthermore, to be able to pursue circulation dynamics down into the submesoscale and nearshore zone, successive levels of grid nesting are essential to convey larger-scale information down to finer-scale flows (Fig. 2). Mason *et al.* (2010a) reports our current techniques with respect both to the mathematical algorithm for the boundary conditions, and to the techniques of data preparation and grid construction that allow for open boundaries to successfully transmit information in and out of the embedded domain. In the following subsections are several examples of clean simulation results with multi-level grid nesting. In addition, we are beginning to explore two-way nested solutions with inner-domain currents feeding up-scale to outer-domain currents (jointly with Dr. Laurent Debreu of Grenoble).

Advection Accuracy: In oceanic models with turbulent flow, accurate advection algorithms are needed, but even the best ones have important non-conservative effects either directly through the discrete advection operator or indirectly through artificial diffusion to control grid-scale error accumulation. When the diffusion crosses interior isopycnal surfaces, this leads to undesirable water-mass errors in long-time simulations. An improved algorithm uses a conservative advection operator with explicit eddy diffusion along isopycnal surfaces. Benefits of this approach were shown in a preliminary way in Marchesiello *et al.* (*Ocean Modelling*, 2009), and we have extended it with a biharmonic diffusion operator that is unconditionally stable in its time stepping (Lemarie *et al.*, 2010). This work takes advantage of the recent reformulation of the equation of state in ROMS (Shchepetkin and McWilliams, 2010), allowing an accurate computation of the neutral-density slopes, and a revised vertical coordinate that smoothly blends z- and sigma-coordinates, so the uppermost coordinate surfaces are nearly independent of topography and produce vertically uniform resolution that smoothly changes to a stretched terrain-following grid in the abyssal part of the ocean. Finally, we are progressing towards diagnosing *post hoc* the diapycnal mixing through its effects on available and unavailable potential energy.

Barotropic-Baroclinic Mode Coupling: As our uses of ROMS expand to finer spatial resolution, larger vertical velocities, and shallower depths, we have revised the fundamental algorithm of time stepping and barotropic-baroclinic mode coupling. This leads to different options within the splitting algorithm in ROMS, *e.g.,* whether or not to recompute Coriolis and advection terms for barotropic mode at every barotropic time step, or keep them constant (recomputing only at every baroclinic time step), while providing proper time-centering for them (via forward extrapolation to avoiding time lag) to ensure numerical stability and efficiency of the overall splitting algorithm (Fig. 1).

Mesoscale Eddies: A virtue of nested regional models is that they can feasibly simulate mesoscale eddies without the difficult compromise in resolution imposed by the expense of global models. We exploit this in several regions listed in the preceding section. For the California Current System we have devised an eddy detection and tracking algorithm to determine the population characteristics

(Kurian *et al.*, 2010). For example, most long-lived, large cyclones have their core at the surface and are widely distributed in their birth sites; in contrast, most anticyclones have a subsurface core and are commonly born in the California Undercurrent. Time- and volume-averaged eddy buoyancy and tracer fluxes play a controlling dynamical role in most boundary currents and dominate lateral mixing over weeks and months. Off Peru, around the recent VOCALS experiment, lateral eddy heat flux is essential to transfer cold water from coastal upwelling and thus to maintain the cold surface necessary for the extensive offshore stratus cloud deck (Colas *et al.*, 2010a). For both North and South America, we are currently diagnosing the eddy buoyancy fluxes and eddy-induced Lagrangian mean circulation (bolus velocity; Colas *et al.*, 2010b); these quantities are much discussed by dynamicists but rarely measured nor successfully diagnosed in models, mainly because of sampling estimation errors.

Topographic Delicacy and Model Uncertainty Estimation: There are many potential causes for simulation uncertainty and imprecision, both in ocean and climate models (Neelin *et al.*, 2010). We are now devising and evaluating test-bed problems for their systematic exploration in ROMS (Approach section). It is clear, though, that complex topography both has very big effects on circulation, even in the upper ocean near coasts, and is a primary source of uncertainty, in part because topography cannot be fully measured. These effects are manifested in separating currents and persistent alongshore standing eddies. One example is the separation and "wake" instability of the California Undercurrent just south of Monterey Bay; a measure of its importance is a very large topographic form stress across the ridge at the separation site (Fig. 3). Better known examples are the boundary separation locations of, *e.g.,* the Gulf Stream and Kuroshio currents which we are simulating with high-submesoscale resolution through nesting (Fig. 4).

Upper-Ocean Submesoscale Currents: Submesoscale currents are abundant in the upper ocean because of frontogenesis and filamentogenesis induced by neighboring mesoscale eddies and "mixed-layer" baroclinic instability. Regional simulations spontaneously develop $\sim$ 0.1-10 km features with strong velocity and even stronger tracer gradients and vorticity. A comparison between California and Peru in different seasons (Fig. 5) shows that the dominant patterns, hence dynamical processes, occur with different regimes. The Gulf Stream and its Rings (Fig. 4) show further morphological differences, with geographically and temporally distinctive submesoscale lateral mixing. Inspired by these discoveries of submesoscale transitions, we have made theoretical studies of frontal instability during frontogenesis, cold-filamentogenesis, and the arrest of continuing frontogenesis by its own cross-frontal eddy flux and secondary circulation (McWilliams, *et al.*, 2009b,c; McWillams and Molemaker, 2010).

Topographic Submesoscale Currents: The other major cause of submesoscale currents is mean or mesoscale flow along a sloping bottom. The bottom boundary layer causes vertical shear, and against a slope this implies horizontal shear and vertical vorticity. When the current encounters a ridge or canyon, separation often occurs and, as with wakes, violent instabilities ensue after separation into the interior. These instabilities are often submesoscale and lead to local diapycnal mixing and energy dissipation as well as submesoscale coherent vortex generation (Molemaker *et al.*, 2010b). Examples are the equatorward slope current north of the Gulf Stream ($z = -500$ m in Fig. 4), and all along the continental margin of the U.S. West Coast even in the abyss (Fig. 6). The phenomenon extends into the open ocean along escarpments and over sea mounts, hence is quite widespread. It is a generic process that has received too little attention in most ocean models. In

particular, it may control the boundary stress and separation behavior for the major ocean currents, acting both at the mesoscale and submesoscale (Fig. 3).

Internal Tides: Internal tides are spatially irregular due to their generation by astronomical tidal currents over especially favorable topographic slopes. We have investigated the generation in the Luzon Strait and subsequent propagation into the South China Sea and, more weakly, the open Pacific (Buijsmann *et al.*, 2010a,b). The timing of highly nonlinear internal wave emission is related to particular phases of multiple astronomical harmonics, and the east-west asymmetry of emission is due primarily to topographic shape and secondarily to the Kuroshio pycnocline slope. In the Southern California Bight, internal tides measured on the shelf (*e.g.,* off Huntington Beach in 2006) are primarily due to remote generation in deep basins around the Channel Islands (Fig. 7; Buijsmann *et al.*, 2010c). In special hot-spots the generation rate is nearly as large as in the better known internal tides over the Hawaiian Ridge; this makes it likely that there are presently many undiscovered hot-spots around the world that can be simulated only with high-resolution regional models.

Lagrangian Dispersal: We made an 11-year reanalysis of the Southern California Bight with fine resolution ($dx = 1$ km) and did extensive statistical assessments of its skill with measurements (Dong *et al.*, 2009a). Lagrangian trajectories calculated from this simulation are synthesized into a "connectivity matrix" for the probability of departure and arrival between all pairs of shoreline locations (known as retention and recruitment among larval biologists). It shows considerable spatial inhomogeneity, and it provides more statistical regression skill for regional species distribution and temporal fluctuation than do any other environmental variables yet tested (Mitarai *et al.*, 2009; Watson *et al.*, 2009, 2010).

Shelf and Nearshore Waves and Currents: On the continental shelf in the Bight, Lagrangian dispersal (*e.g.,* of urban sewage out-fall) is usually dominated by topgraphically generated submesoscale currents with occasional big sweeps by passing mesoscale eddies. In addition, shoreline breaking surface gravity waves drive littoral currents. We have finally completed our development of ROMS with 3D wave dynamical and mixing effects (Uchiyama *et al.*, 2010) to be able to examine eddy-littoral interactions, especially for material dispersal (*e.g.,* is there a zone of "sticky water" just outside the surf?). An early result is the simulation of the Duck, NC, littoral currents with realistic topography, showing strong, unstable rip currents with an offshore extent that increases with the amplitude of the incident waves (Fig. 8).

Oceanic Surface Boundary Layer: Surface gravity waves have important influences on boundary layer turbulence, primarily through the Stokes-drift vortex force that engenders Langmuir circulations, but also through momentum and energy impulses in breaking waves (Sullivan and McWilliams, 2010). Jointly with Peter Sullivan at NCAR, we are using Large Eddy Simulations (LES) to test parameterization ideas about the vertical mixing effects in wavy Ekman layers. In a more experimental mode we find that disequilibrium wind-wave conditions modify the Langmuir circulations, most notably by greatly extending their longitudinal correlation length when the waves are bigger than consistent with local wind generation. We have developed a new model for bubble concentrations including breaker injection, size evolution, and dissolved gas exchanges (Fig. 9; Liang *et al.*, 2010). It is now being applied to wave-tank experiments by Grant Deanne at Scripps and incorporated into fully turbulent LES simulations.

IMPACT/APPLICATIONS

Geochemistry and Ecosystems: An important community use for ROMS is biogeochemisty: chemical cycles, water quality, blooms, micro-nutrients, larval dispersal, biome transitions, and coupling to higher tropic levels. We collaborate with Profs. Keith Stolzenbach (UCLA), Niki Gruber (ETH), Curtis Deutsch (UCLA), and David Siegel (UCSB) on these topics.

Data Assimilation: We collaborate with Drs. Yi Chao (JPL) and Kayo Ide (U. Maryland) by developing model configurations for targeted regions and by consulting on the data-assimilation system design and performance. Current, quasi-operational, 3DVar applications are in Monterey (AOSN, ASAP), California more broadly (SCCOOS and CenCOOS), and Alaska (Prince William Sound). We are starting to develop the Local Ensemble Transform Kalman Filter technique — a more efficient alternative to 4DVar methods with most of the benefits compared to 3DVar — to obtain solution-adaptive, time-evolving estimations with ROMS.

TRANSITIONS

ROMS is a community code that has widespread applications (http://www.myroms.org).

RELATED PROJECTS

The Community Sediment Transport Model (CSTM) is a NOPP and ONR project that is based on ROMS. We are participating as code prototypers and application testers.
Three Integrated Ocean Observing System (IOOS) regional projects for California and Alaska (SCCOOS, CenCOOS, and AOOS) are utilizing ROMS for data assimilation analyses and forecasts.
We are participating in VOCALS, which is a CLIVAR and NSF project to investigate coupled regional climate processes of the west coast of South America.

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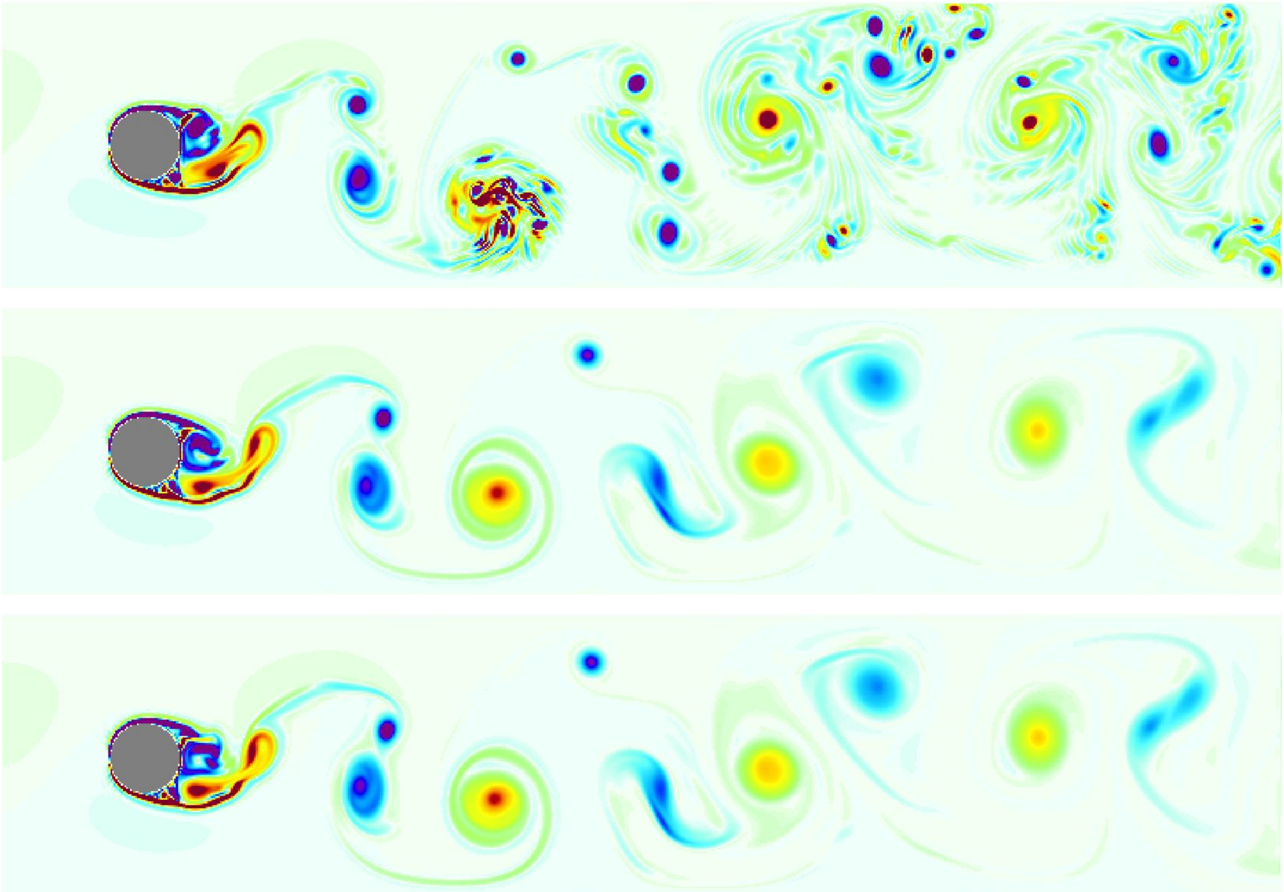

Figure 1: ***Illustration of mode-coupling instability due to improper treatment of "slow" terms – Coriolis and advection – within the barotropic mode. The model problem is barotropically dominated flow past a cylindrical obstacle, posed and solved as ROMS 3D problem,*** *i.e.,* ***using mode splitting. Shown is the normalized vertical vorticity,*** ζ^z/f. *Upper panel:* ***Coriolis and advection terms are computed only during baroclinic time steps (effectively at time step*** n***) and kept constant during barotropic stepping. Baroclinic time step*** $\Delta t = 360\,s$***, mode splitting ratio 82; depth*** $h = 500\,m$***; horizontal resolution*** $\Delta x = \Delta y = 500m$***; inflow velocity specified at open boundary on the left*** $u = 15\,cm/s$ ***(advective Courant number 0.1). Grid dimensions are*** 720×160***.*** *Middle:* ***same as above, except that vertically-integrated Coriolis and advection terms are extrapolated half-step forward in time;*** *Bottom:* ***same as*** *middle,* ***but*** $\Delta t = 600\,s$ ***and mode splitting ratio 136. All three runs were started from a common initial conditions file with fully-developed island wake pattern, and run for 17 model days during which the disturbances detached from the obstacle leave the computational domain (***$L = 360\,km$***) through the open boundary on the right. Note that the two lower panels show very little difference, and, in fact, even little decorelation for this inherently unstable flow. This illustrates robustness, and in fact, insensitivity of the code to time step size, up to the limit of advective stability. The upper panel corresponds to the settings where the code is unconditionally unstable, however the use of third-order upstream-biased scheme for momentum advection mitigates (in fact, "masks out") the instability by shifting the scales of maximum growth rate away from minimum size resolved by the grid. As the result, the first manifestation of numerical instability is the non-physical growth of vorticity maxima of the detached vortex cores, rather than appearance of grid-scale oscillations or checkerboard patterns more common for other types of numerical instabilities. (Figure from Shchepetkin)***

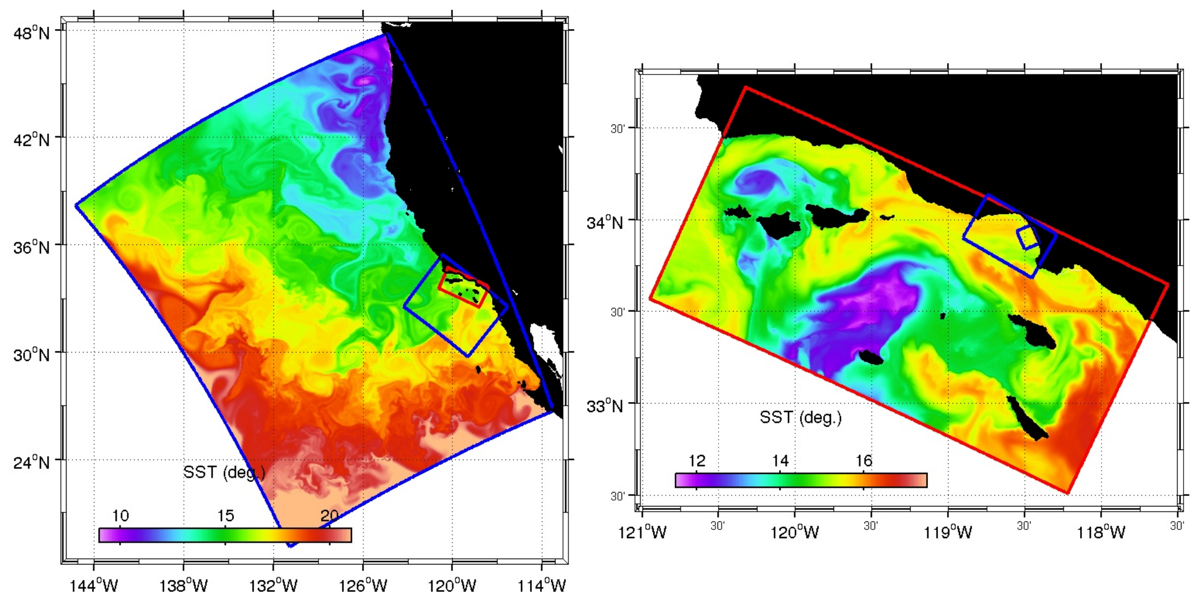

Figure 2: ***Snapshot of SST in successive grid nests starting at the scale of the Eastern Subtropical Pacific ($dx = 4$ km) descending down, in this application, to Santa Monica Bay ($dx = 30$ m). It is used to simulate local phenomena of mesoscale and submesoscale eddies, internal tides, and nearshore surface wave breaking and rip currents Uchiyama** et al.**). The methodology is most recently explained in Mason** et al.** (2010a). (Figure from Uchiyama)***

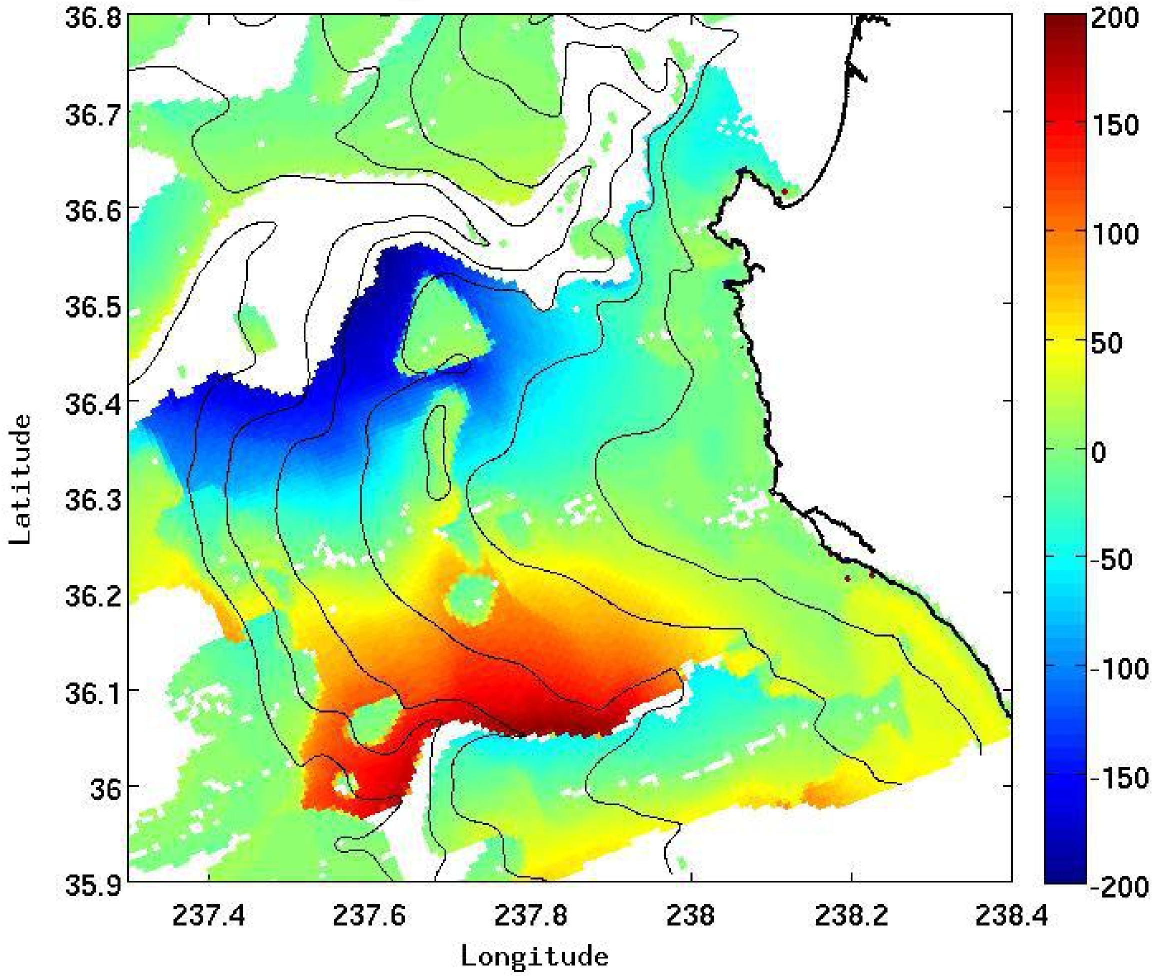

Figure 3: ***Summertime-mean bottom pressure anomaly [N m^{-2}] across the ridge extending offshore of Pt. Sur, California, south of Monterey Bay. This is a site of offshore separation of the poleward California Undercurrent. Both the positive and negative lobes of the bottom pressure, when multiplied by an alongshore topographic slope, yield an equatorward form stress of about 5 N m^{-2} when integrated over the local area of the current; this is many times larger than the local wind stress. Associated with the separating Undercurrent is a vigorous, submesoscale, centrifugal instability that recurrently leads to the generation of offshore, mesoscale California Undercurrent eddies (Cuddies). (Molemaker*** et al.***, 2010b).***

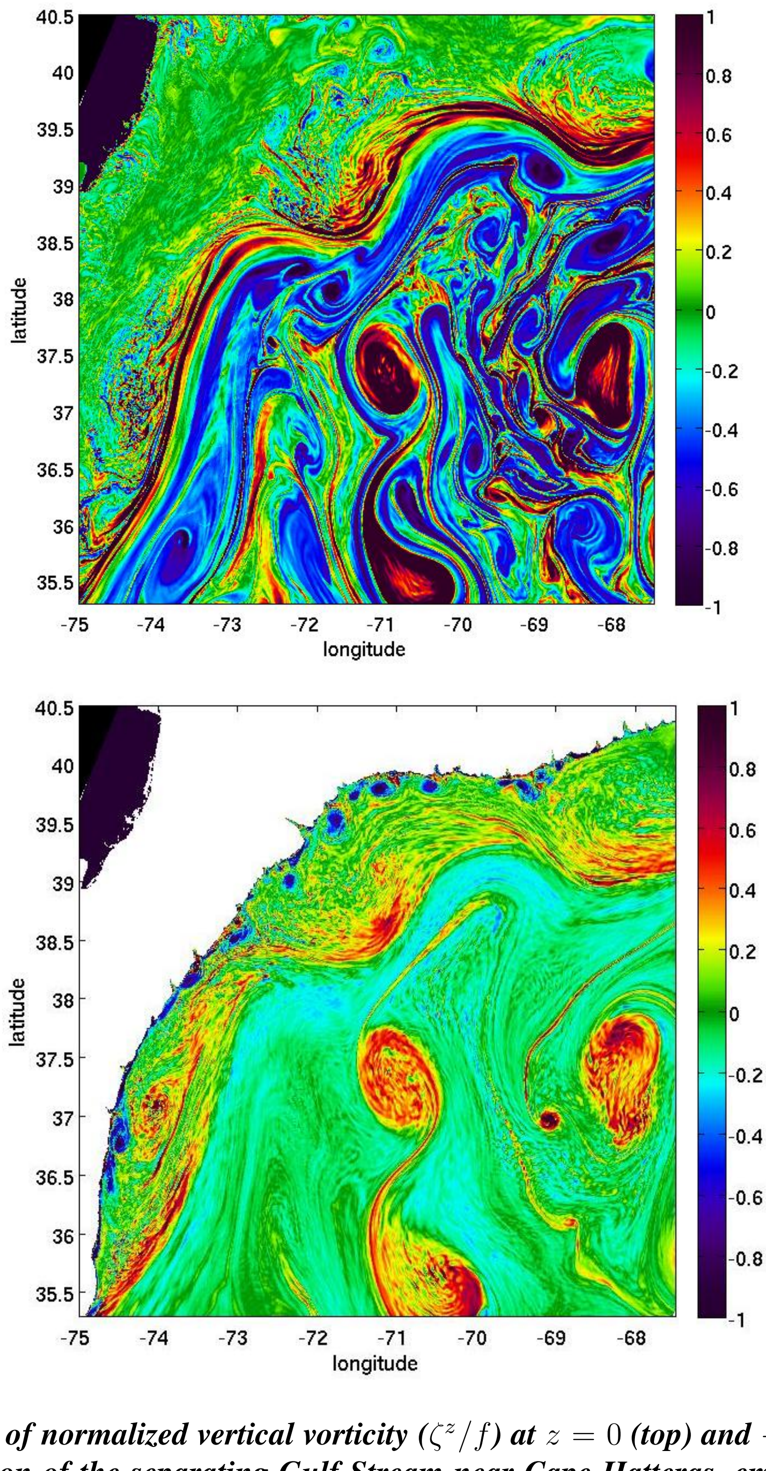

Figure 4: ***Snapshot of normalized vertical vorticity*** (ζ^z/f) ***at*** $z = 0$ ***(top) and*** -500 ***m (bottom) in a regional simulation of the separating Gulf Stream near Cape Hatteras, embedded in an eddy-resolving North Atlantic domain. Notice the submesoscale instabilities,*** *e.g.,* ***on the north wall of the Stream and within cyclonic Rings. Also, notice the topographic generation of submesoscale anticyclones against the continental slope. The surface-layer submesoscale currents are the dominant influence on lateral tracer mixing over horizontal scales of 0.1-10 km. (Figure from Molemaker)***

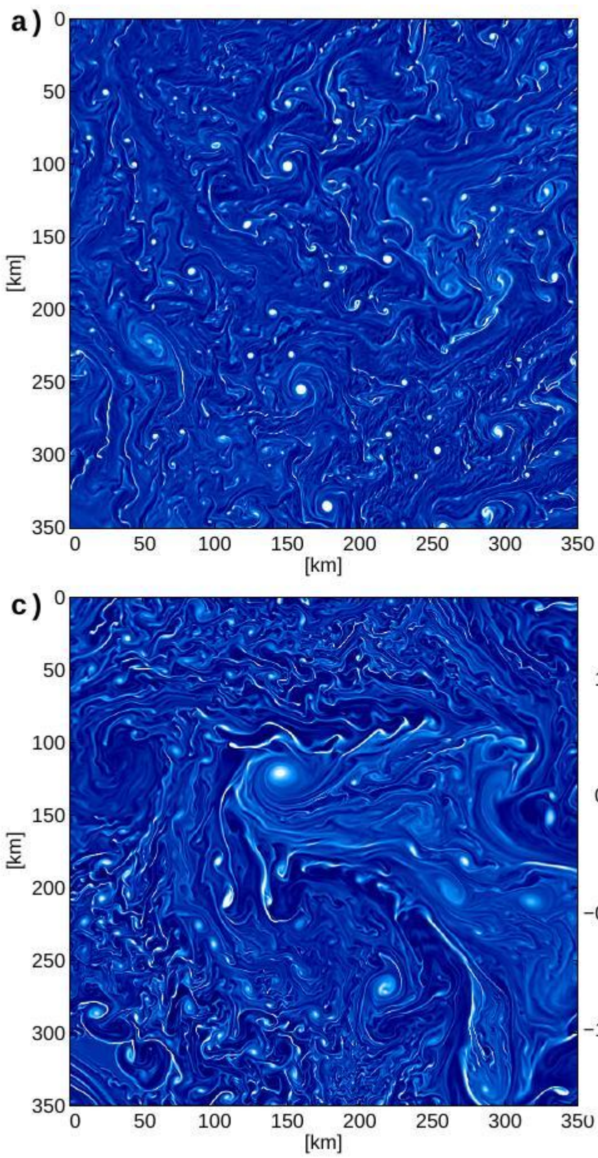

Figure 5: ***Snapshot of normalized vertical vorticity (ζ^z/f) at the surface off Peru (top row) and California (bottom) in winter (left column) and summer (right). The visible features are primarily submesoscale, although the organizing mesoscale eddies can be perceived in the background. There is strong regional and seasonal variability in the intensity and morphology of the submesoscale flows. In California the flows are primarily frontal, especially in summer when they are especially unstable, whereas in Peru the cold filaments are very strong (note the different scale) and produce many coherent vortices. (Figure from Colas)***

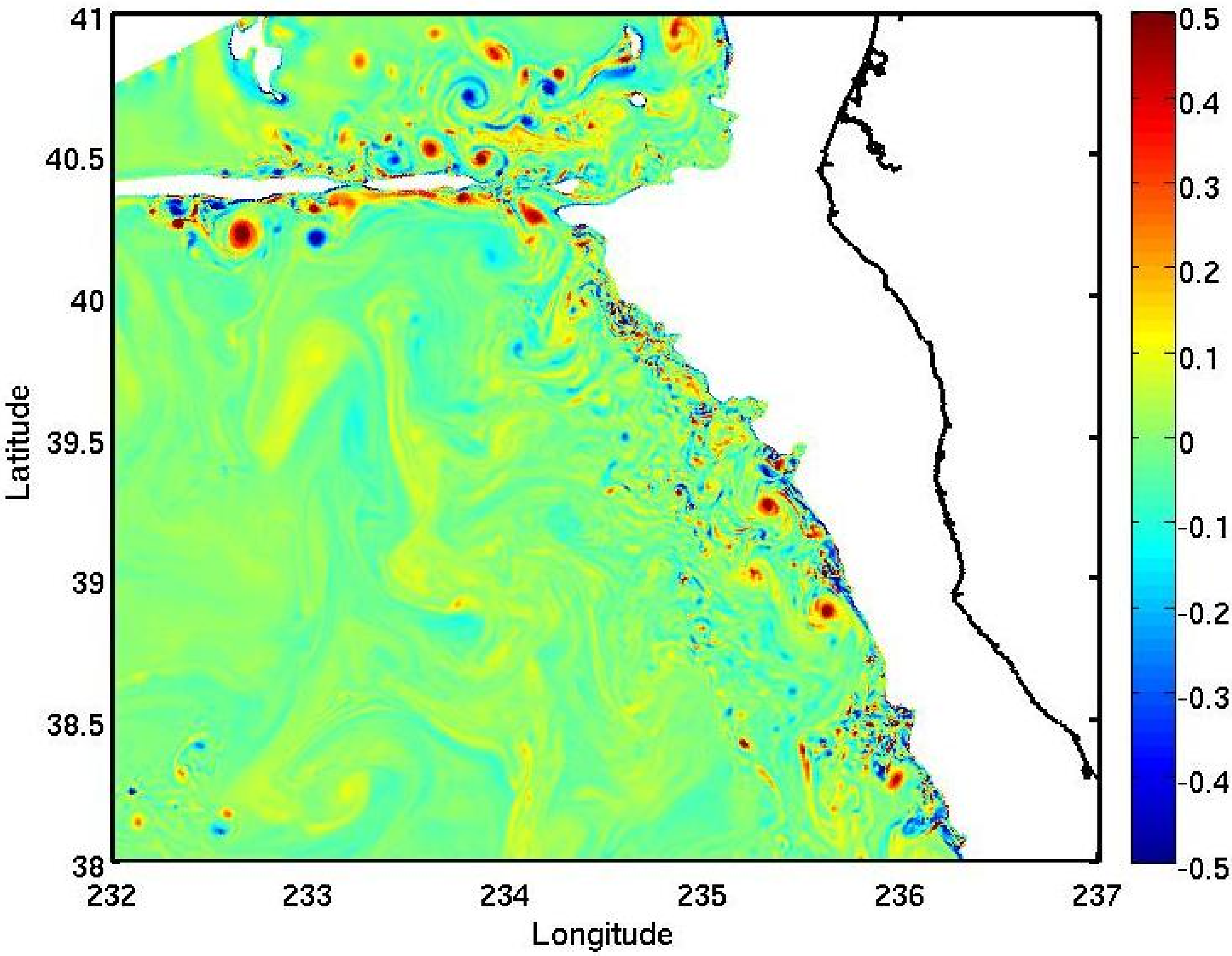

Figure 6: ***Snapshot of normalized vertical vorticity (ζ^z/f) at $z = -2500$ m from Pt. Reyes (38°N) past Cape Mendocino (40.4°N). Vorticity generation occurs through abyssal currents dragging against topographic slopes. This leads to strong near-boundary diapycnal mixing, even outside the turbulent bottom boundary layer, and it then evolves into a population of long-lived submesoscale coherent vortices. In addition to the high activity along the base of the continental slope, notice the Mendocino escarpment (40.5°N) and the seamount complex (232°E, 38°N). (Figure from Molemaker)***

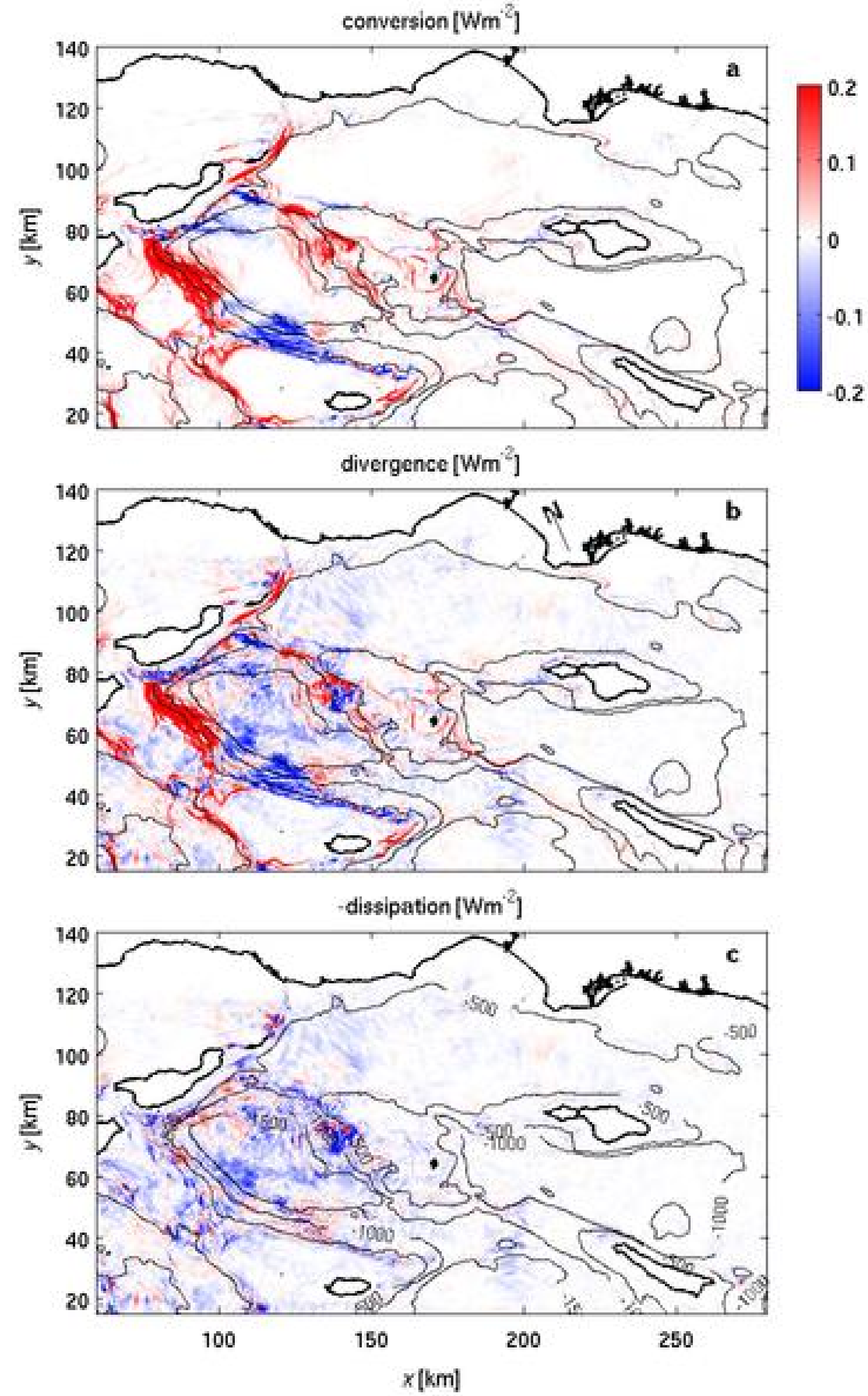

Figure 7: ***Mean energy balance for semi-diurnal internal tides in the northwestern Southern California Bight: generation, transport (flux divergence), and dissipation rate (Buijsmann** et al.**, 2010c). The "hot-spot" south of the Channel Islands has a generation rate comparable to what occurs over the Hawaiian ridges. Much of the generation is transported to other areas, with only a small fraction causing local dissipation.***

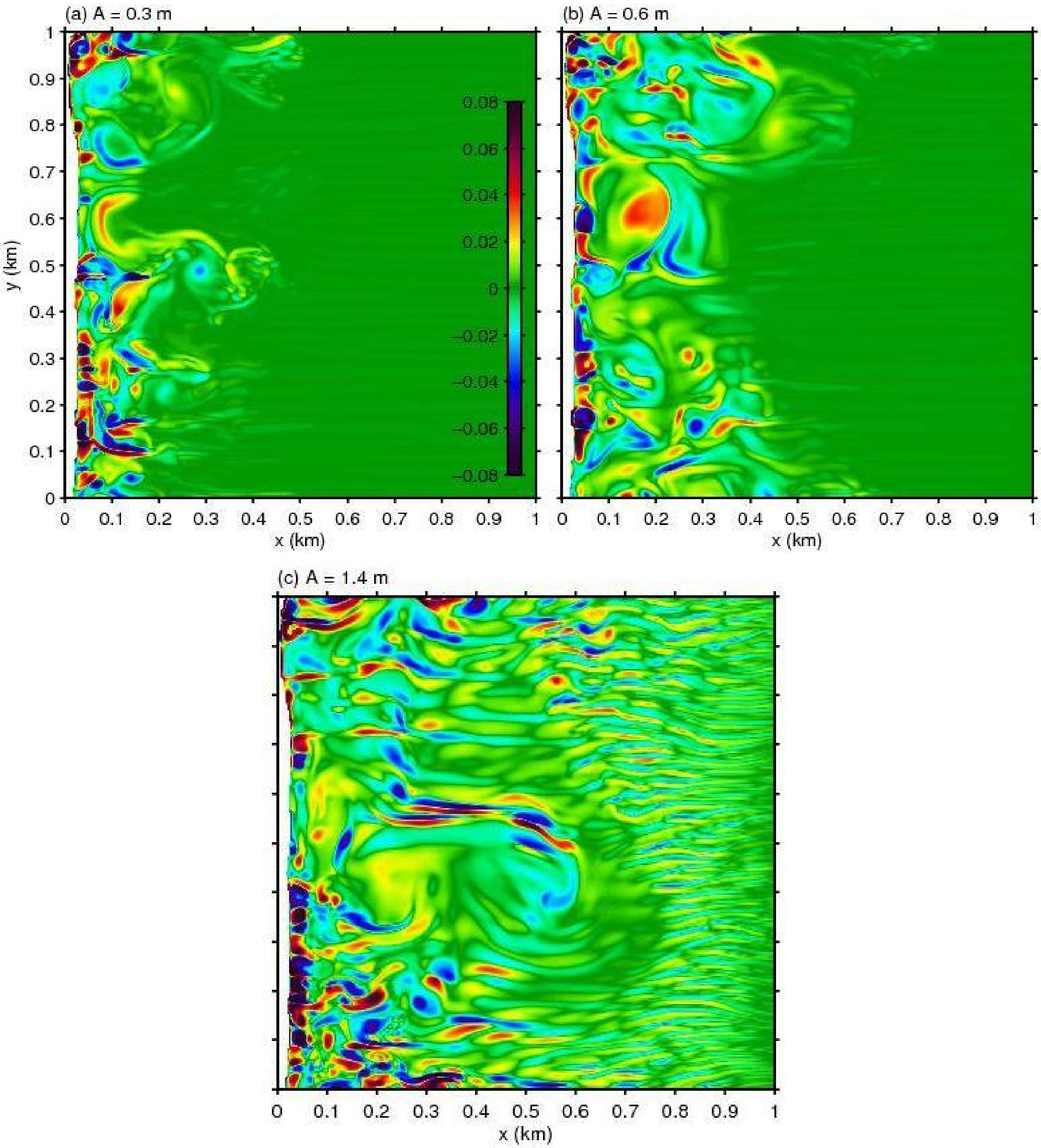

Figure 8: ***Snapshots of vertical vorticity, ζ^z [s^{-1}], in rip currents over the measured topography at Duck, NC, for three different sea-level amplitudes A [m] of incoming surface gravity waves that approach the mean shoreline in a normally incident direction. The irregular topography has the effect of making the littoral currents almost always unstable and unsteady, even when the incident waves are steady. The offshore extent of the littoral currents increases with bigger waves. In the high-wave case (c) note the transverse stripes in the offshore region: these are Langmuir circulations induced by the surface stress of breaking waves near the shoreline (in contrast to the deep-water process with surface wind stress), plus the effect of Stokes drift. This is calculated with ROMS with a coupled wave-current model (Uchiyama et al., 2010; Uchiyama and McWilliams, 2010).***

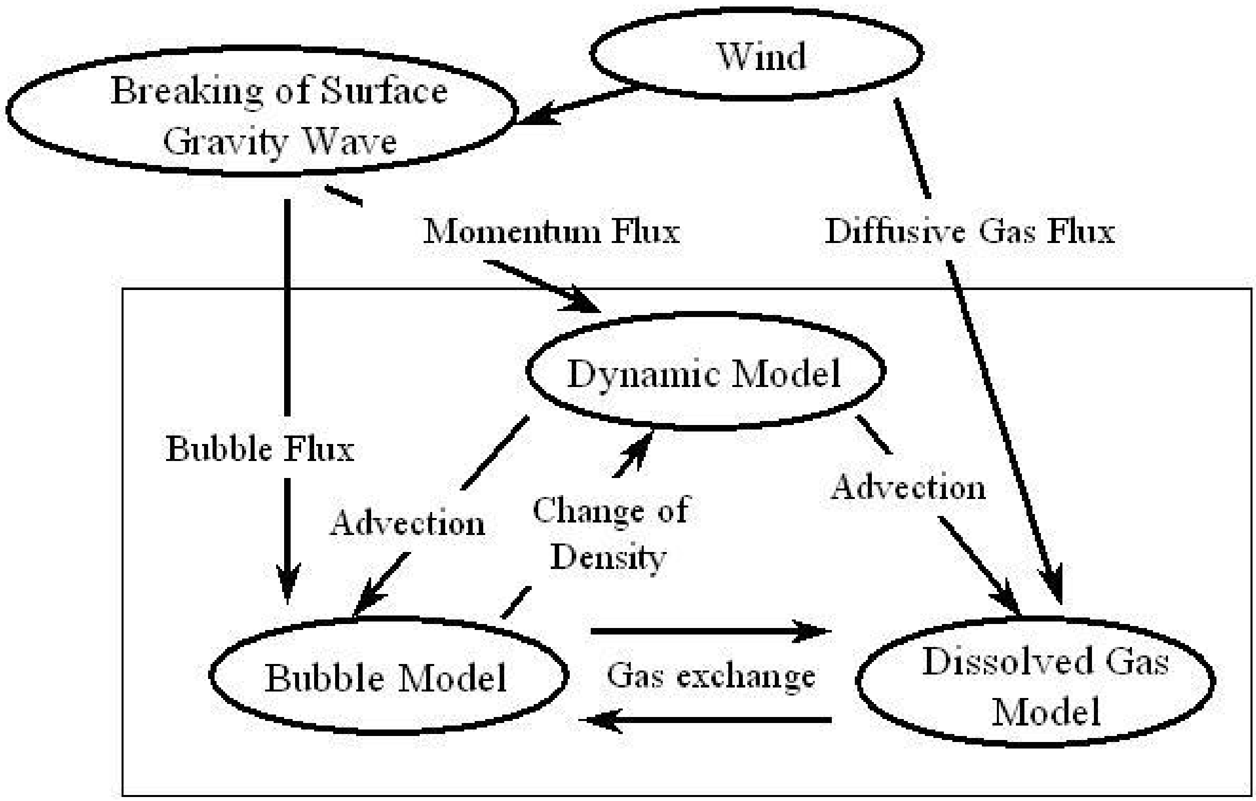

Figure 9: ***Schema for a size-resolved model of bubble concentration in the oceanic surface boundary layer with dissolved gases and air-sea gas exchange (Liang** et al.**, 2010). The dynamic model is Large Eddy Simulation with surface wave effects (Sullivan and McWilliams, 2010).***